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A study of excited states of N(14) from the C(13)(p,n)N(13) reaction.

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Robert Edward Adamson

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by

ROBERT EDWARD ADAMSON, JR.
COURSE VIII

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by

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S.B., United States Naval Academy
(1943)

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

The excitation curves for the emission of neutrons and gamma rays from the disintegration by protons of the C^{13} in 62% enriched KCN were investigated. The threshold for neutron emission was observed at 3.25_6 Mev ± 1% and a resonance was obtained at 11.04 Mev ± 1% with a width at half resonance of 45 ± 20 Kev. Definite indications of a second resonance were obtained at 11.21 Mev ± 3%. The neutrons from C^{13} were shown to come from the $C^{13}(p,n)N^{13}$ reaction. No resonances were obtained for gamma ray emission from C^{13}.

The threshold of the excitation curve of a thick, pure carbon target was obtained at 3.26 Mev ± 1%. There was no activity of any kind induced in tantalum with protons of energies up to 3.96 Mev ± 1%. Potassium metal and unenriched KCN gave no evidence of any reaction to protons.

ABSTRACT

The excitation curves for the emission of neutrons and gamma rays from the bombardment by protons of the C^{13} in [illegible] were investigated. The threshold for neutron emission was observed at 3.23_5 Mev ± 1% and a resonance was obtained at [illegible] Mev ± 1% with a width at half maximum of [illegible] ± 20 kev. Definite indications of a second resonance [illegible] at [illegible] Mev ± 1%. The neutrons from C^{13} were shown to come from the $C^{13}(p,n)N^{13}$ reaction. No resonances were obtained for gamma ray emission from C^{13}.

The threshold of the excitation curve of a thick, pure carbon target was obtained at [illegible] Mev ± 1%. There was no activity of any kind induced in tantalum with protons of energies up to [illegible] Mev ± 1%. Potassium metal and unenriched KCl gave no evidence of any reaction to protons.

ACKNOWLEDGMENTS

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I wish to thank Professors Clark Goodman and W.W. Buechner for their supervision and encouragement during the experimentation and the preparation of this thesis. Dr. W.M. Preston, H.B. Willard, and P.H. Stelson assisted in the operation of the Rockefeller Generator, giving freely of their time. Lieutenant Commander W.D. Baker and Lieutenant J.S. Howell assisted in the taking of the data. Professor T.S. Gray and H.B. Frey were of great assistance in the design, construction, and operation of the equipment. My gratitude also is due all members of D.I.C. Projects 6555 and 6663 at M.I.T. for their unfailing cooperation during all phases of the investigation. Mrs. Margaret Courant typed the report.

CHAPTER I

INTRODUCTION

Crane and Lauritsen observed neutrons from the bombardment of ordinary carbon with deuterons in 1935 (Cr 35), and since then considerable information has been amassed regarding the levels of $(N^{14})^*$ from the reaction,

$$C^{12} + d \longrightarrow (N^{14})^* \longrightarrow N^{13} + n + Q_1 .$$

In 1936, Bonner and Brubaker reported a Q_1 value of -0.37 Mev for this reaction (Bon 37), subsequently recalculated by Bonner as -0.25 ± 0.03 Mev (Bon 38). In 1947, Bennett and Richards found the threshold $Q_1 = -0.27 \pm 0.02$ Mev (Ben 47).

Bonner and Hudspeth, at the Rice Institute, discovered resonances for neutron emission at 0.92, 1.13, and 1.30 Mev (Bon 40a). The Rice group, in later investigations, corrected and amplified this information, giving resonances for neutron emission from $(N^{14})^*$ at 0.92, 1.16, 1.30, 1.74, and 1.82 Mev (Bon 40b), (Ben 41). Bailey, Phillips, and Williams verified these levels (Bai 42). The information regarding these excited levels has been summarized by Hornyak and Lauritsen (Ho 48). Bailey _et al._, in a more recent investigation, were unable to confirm the existence of the resonance at 1.15 Mev (Bai 48).

The level values given by Hornyak and Lauritsen were re-

calculated using the new value for the mass of the neutron = 1.00898 amu (Ev 48), the Cornell University group mass values (Cor 47), and Bonner's values for the deuteron energies for resonances for neutron emission of 0.92, 1.16, and 1.30 Mev, giving $(N^{14})^*$ levels at 11.05, 11.24, and 11.35 Mev. Since the level values of 11.05, 11.26, and 11.37 Mev given in Hornyak's and Lauritsen's summary were average values, the latter values were used for comparison purposes.

It is generally accepted that the energy levels of a nucleus are the same, regardless of the process by which the nuclide is formed, provided selection rules do not prohibit transitions to such levels (Br 36), (Bet 37), (Bet 47).

Early investigations of another reaction yielding the same compound nucleus,

$$C^{13} + p \longrightarrow (N^{14})^* \longrightarrow N^{13} + n + Q_2 ,$$

were confined to measurement of the threshold Q_2 value reported as -2.97 ± 0.03 Mev by Haxby et al. (Hax 40a,b). In 1950, Richards and Smith reported the threshold as 3.236 Mev ± 0.1% (Ri 50), using the Herb evaluation of the $Li^7(p,n)Be^7$ threshold of 1.882 Mev ± 0.1% as a standard (He 49). The corrected threshold value gave $Q_2 = -2.987 \pm 0.1\%$.

The recent installation of a positive-ion source in the 1-5 Mev Rockefeller Generator has made possible the extension of nuclear studies to higher voltages than have been possible with most electrostatic machines. At the suggestion, and with the assistance, of Professor W.W. Buechner, the $C^{13}(p,n)N^{13}$ reaction has been studied. Information regarding the energy levels of $(N^{14})^*$ obtained from the

$C^{13}(p,n)N^{13}$ reaction allows a direct comparison with the levels of $(N^{14})^*$ from the $C^{12}(d,n)N^{13}$ reaction.

The companion gamma ray reaction,

$$C^{13} + p \longrightarrow (N^{14})^* \longrightarrow N^{14} + \gamma + Q_3 ,$$

with a Q_3 value of 7.56 Mev (Ho 48), was also studied to obtain additional information regarding the levels of $(N^{14})^*$. Previous experimentation had shown that a resonance level for gamma ray emission occurred at a proton energy of 554.0 ± 2 Kev (Ro 38), (Cu 39), (Fo 49). Van Patter recently discovered another level for the same reaction with a proton energy of 1.697 ± 0.012 Mev (Va 49).

Calibration of the generator was required to give an accurately known proton energy. Enriched carbon was obtained in the form of potassium cyanide (KCN, 60-62% C^{13}). Tantalum, potassium, and unenriched KCN were also studied in order to ascertain the extraneous effects, if any, introduced by nuclides other than C^{13}. To corroborate the reaction, the production of N^{13} ($\tau_{1/2}$ = 9.93 ± 0.03 min. (Wa 39)) was observed by means of the annihilation radiation which accompanies its positron decay.

CHAPTER II

APPARATUS

The Detecting Circuit

The detecting equipment was capable of determining both neutron and gamma ray yields, singly and combined in simple and delayed coincidence measurements.

A small, cathode-follower preamplifier (Fig. A-1) was constructed in order that the output signal from the enriched BF_3 proportional counter could be transmitted a considerable distance along the delayline, without distortion and with a minimum of attenuation of the output signal.

An investigation of the available delay line revealed that type RG65U was satisfactory for fast delay circuits because of its inherent time delay of 0.042 μ seconds per foot. Moreover, its high input impedance of 1000 ohms was desirable (Bla 49). The selection of RG65U dictated the use of a 1000 ohm resistor in the cathode-follower of the preamplifier and an equivalent 1000 ohm input resistance in the amplifier. The RC equivalent circuit of the delay line served as a differentiating circuit. The literature indicated W.C. Elmore's fast amplifier (El 49a,b) was nearly ideal for the amplifier (Fig. A-3). The original Elmore circuit was used in the first four stages but a slight modification in the LC shunt and series peaking circuits of the fifth stage was required in order to drive a negative signal into the

coincidence circuit (Fig. A-4). In addition, the final stage was modified so that a signal might be relayed to a scaling circuit for single channel counting, without affecting the output to the coincidence circuit.

To obtain coincidences, a conventional Rossi coincidence circuit was constructed (Ko 46), modified so the plate load of the input tubes was a single length of RG65U delay line. Both tubes of the coincidence circuit were conducting unless a signal from one of the preceding Elmore amplifiers was capable of cutting off a tube. The signal from the plate circuit (Fig. A-4) of a coincidence tube was impressed upon the grid of a discriminator tube biased so only simultaneous ($\pm$ 0.042 seconds) cutting off of both coincidence tubes caused an input signal (to the discriminating tube) to exceed the negative bias voltage (-9.0 volts), which in turn allowed the discriminating tube to fire. The negative signal of the discriminating tube was led into the amplifier half of a 12AT7 twin triode tube and then into the cathode-follower half of the same tube, which drove the coincidence scaler.

The gamma ray apparatus preceding the coincidence circuit was identical to that of the neutron circuit except that a 5819 RCA photomultiplier with attached anthracene crystal was used as a scintillation counter (Fig. A-2). A conventional photomultiplier stage with 1200 volt input and 79 volt potential between dynodes was used. This stage led directly to the preamplifier.

Figure A-5 is the complete block diagram of the electronic equipment.

Extensive use of by-pass condensers, germanium rectifiers, and approved construction techniques involving short shielded leads

produced duplicate basic circuits having inherent rise times of $\lesssim 0.05$ μseconds. Moreover, the preamplifiers and amplifiers were capable of a gain of ~ 750, while the output of the coincidence circuit (discriminating tube and driving twin triode included) gave an over-all gain of about one-third.

A Geiger-Mueller tube was used for the detection of gamma rays when the fast neutron counting rate of the scintillation counter was considered appreciable.

The construction and testing of the above equipment was a joint project initiated and completed by W.D. Baker, J.S. Howell, and the author, and a complete description of the apparatus, together with operational curves, circuit analysis, and other data have been presented in the thesis by Baker and Howell (Ba 50).

The Rockefeller Generator

This machine has been modified to provide protons and deuterons of energies varying from about 1-5 Mev as bombarding particles for nuclear reactions. The beam is vertically accelerated through an 8 foot tube into a deflection chamber, where it is bent to a horizontal direction by an analyzing magnet. Energy control of the nuclear missiles is provided by manual control of the magnet current. Adjustment of the entrance and exit slits gives energy resolution of about 0.1%. In the near future, a proton resonance magnetic circuit will be available (Had 49), (Blo 46a,b), (Pa 48). Corona current provides voltage control by varying the spray current. The particle energy is expressed in terms of the generating voltmeter readings. Beam current may be read directly from the target by means of a sensitive micro-

microammeter, or can be integrated and recorded directly in microcoulombs by an electronic beam current integrator. Both stationary and rotating targets may be used. From visual observation, at the target, the beam has a cross section of approximately $\frac{1}{2}$ mm x $\frac{1}{5}$ mm. It should be noted that at the present time (May 1950), dependable operation of the Rockefeller Generator has not been attained for proton energies greater than 3.96 Mev.

One calibration point was provided by the

$$Li^7 + p \longrightarrow (Be^8)^* \longrightarrow Be^7 + n + Q$$

reaction with a threshold of 1.882 Mev (He 49) for a generating voltmeter setting of 40.5 (Wi 50). Using the same nuclear reaction but with singly ionized molecular hydrogen as a bombarding particle,

$$Li^7 + H^+_2 \longrightarrow (Be^8)^* + H^1 \longrightarrow Be^7 + n + H^1 + Q,$$

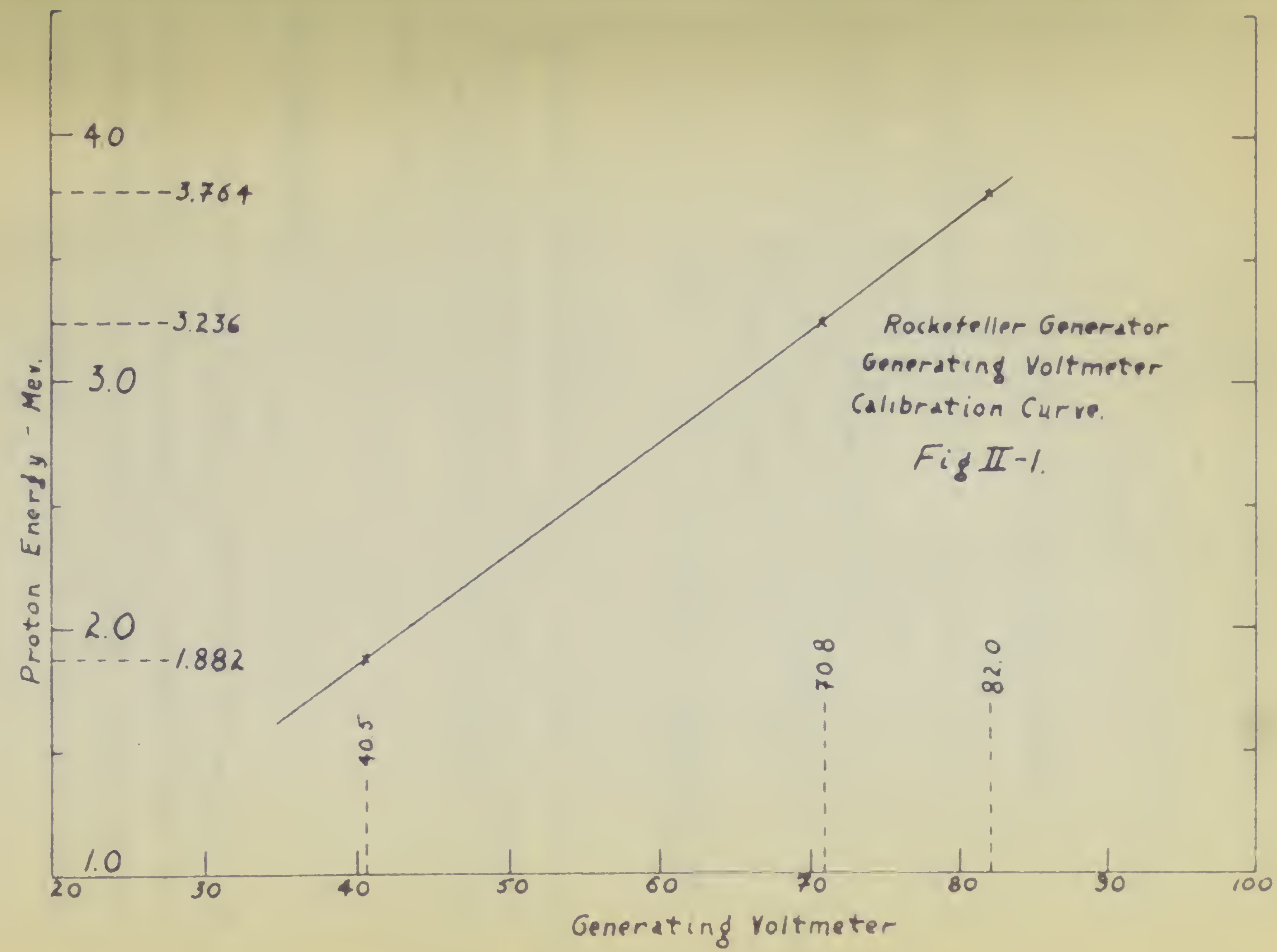
(i.e., passing the mass "two" beam of hydrogen ions through the mass "one" slits), a generating voltmeter reading of 82.0 for the 3.764 Mev threshold was obtained.

Another calibration point was obtained when preliminary investigations using a potassium cyanide target with enriched C^{13} showed that the 3.236 Mev threshold of the

$$C^{13} + p \longrightarrow (N^{14})^* \longrightarrow N^{13} + n \qquad \text{(Ri 50)}$$

reaction occurred at a voltmeter setting of 70.8. (This experiment will be described in Chapter IV.)

The calibration curve (Fig. II-1) obtained from these three points was of sufficient accuracy to allow energy readings to the limit of the actual generating voltmeter (i.e., $\pm$ 10 Kev). The generating voltmeter readings were read with a 100 μ ampere, five inch, one hundred graduation, fan type, 1% accurate microammeter. An operator



Rockefeller Generator
Generating Voltmeter
Calibration Curve.
Fig II-1.

reading this meter could maintain projectile energies within a $\pm$ 10 Kev reading, since the calibration of the microammeter was approximately 47 Kev per graduation.

TABLE II-1

TARGET LOCATION OF THE ROCKEFELLER GENERATOR

Distance from concrete floor	102 cm.	
" " wooden roof	184 cm.	
" " overhead steel I-beam	147 cm.	
" " right wall (concrete)	237 cm.	(looking into the beam)
" " front wall (concrete)	365 cm.	
" " magnet	74 cm. 103 cm.	stationary target rotating target

Electronic recording equipment on the left of the target, at an average distance of approximately 125 cm. from the target, was the background determining factor rather than the left wall at a distance of approximately 350 cm.

The Various Targets

Five different targets were used during this experiment. The individual preparation of each target will be described in the section in Chapter IV pertaining to the actual experiment. The physical characteristics of the various targets are tabulated below for information.

TABLE II-2

TARGET DATA

1. Pure carbon - pressed and rolled graphite - stationary type target

   100% carbon: C^{12} 98.892% (Ni 50)
   C^{13} 1.108% ± 4%

   Obtained from Carbide and Carbon Company

   Total impurities less than one part in a million (Bu 50)

2. Tantalum metal - rotating type target
   sheet tantalum - regular finish annealed - select quality
   approximately 0.350 KG for sheet 0.010" x 3" x 10"

   Chemical analysis of 7 April 1950 (Sp 50):

Ta	99.9%
Fe	0.03% (maximum)
C	0.03% (maximum)

   Obtained from Fansteel Metallurgical Corporation

   FMC Invoice #2R-48290

3. Ordinary potassium cyanide - rotating type target
   assay minimum 95% KCN

chloride((Cl)	0.75%
ferrocyanide ($Fe(CN)_6$)	0.2%
sulfate (SO_4)	0.01%
sulfide (S)	0.003%
sodium (Na)	about 0.1%
heavy metals (Cu, Pb)	about 0.001%

   Obtained from Merck Company 40498

4. Potassium metal - rotating type target
   technical grade

K^{41}	6.91 ± 0.04%	(Ni 50)
K^{40}	0.01119 ± .0001%	
K^{39}	93.08%	

   Obtained from Mallinkrodt Chemical Works

   Accession #4576-X-H

5. Enriched potassium cyanide - rotating type target

grams KCN (82.9%)	1.01
grams KCN (100%)	.83
atom per cent C^{13}	62
grams C^{13} excess	0.10

Obtained from Eastman Kodak Company, OR-2297-8, A-295570

The Various Detectors

The neutron counter was an enriched boron trifluoride proportional counter (Mk2 Mod 25 #951) manufactured by the Radiation Counter Laboratories.

TABLE II-3

BF_3 COUNTER DATA

outside diameter	1 in.
wall thickness	0.042 in., brass
filling	55 cm. Hg of 96% enriched BF_3
operating voltage	2200 v.
center wire	2 mil tungsten
active volume length	10 in.

The counter was inserted in one of two paraffin cylinders encased in cadmium similar in appearance and in physical dimensions to the paraffin cylinder of a conventional long counter (Han 47), except that no holes were provided in the face of the paraffin as described in the reference.

TABLE II-4

DIMENSIONS OF THE LONG COUNTERS

	Cylinder A	Cylinder B
outer diameter	18.0 cm.	20.0 cm.
inner diameter	3.5 cm.	3.2 cm.
length at outer diameter	51.0 cm.	30.8 cm.
length of liner (i.e. inner diameter)	51.0 cm.	49.8 cm.

(Cylinder B was a right cylinder, except that the liner protruded beyond the cylinder base.)

The scintillation counter was a RCA type 5819 photomultiplier tube (RCA 49) with an anthracene crystal roughly thirteen square centimeters in area and approximately fifteen millimeters thick.

The Geiger-Mueller Counter was a 1B85 Thyrode Counter tube manufactured by the Victoreen Instrument Company (Vi 49).

TABLE II-5

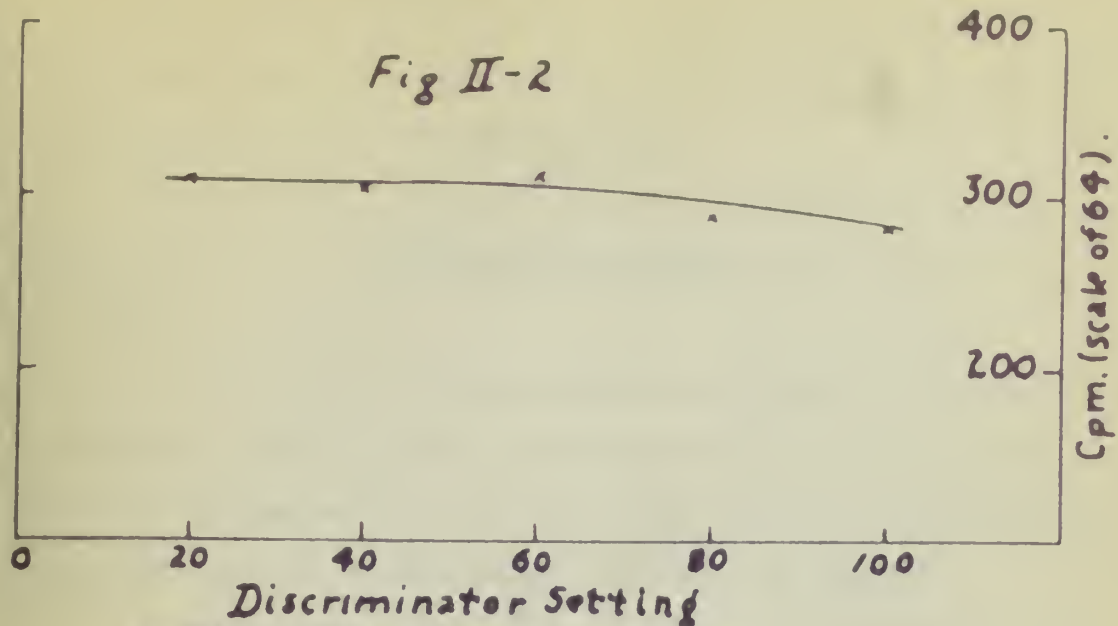
G.M. COUNTER DATA

outside diameter	51/64 in.
wall thickness	30 mg/cm^2 aluminum
active volume length	2.75 in.
operating voltage	790 v.

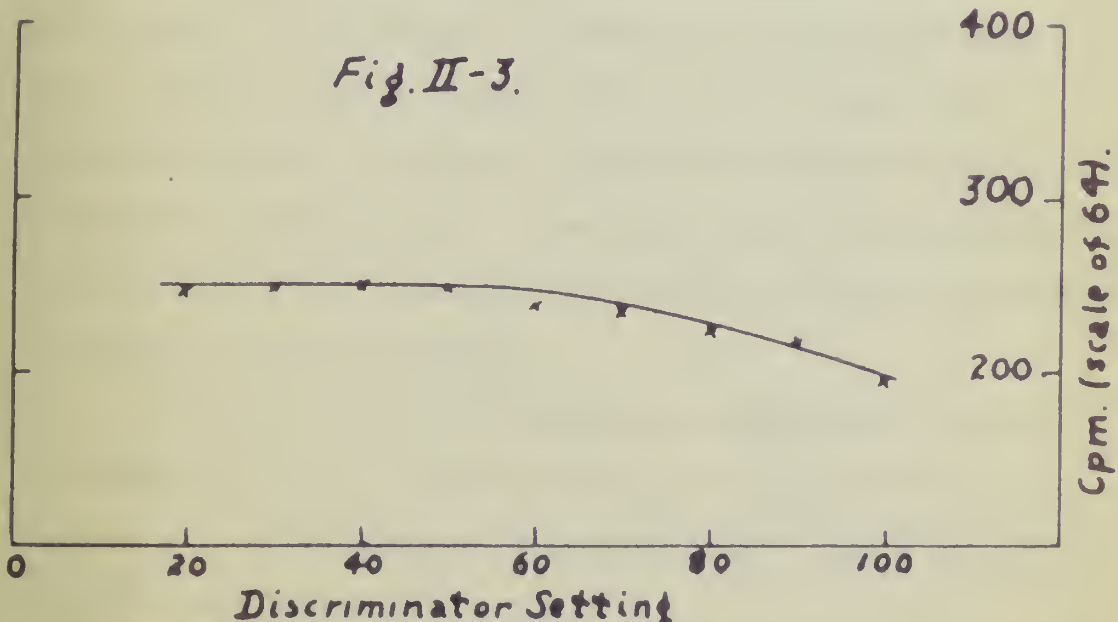
Operating Characteristics

Tests of the individual circuits were made by parallelling the grids of the coincidence tubes and disconnecting the circuit not in use (Fig. A-4). The discriminator of the coincidence scaler was varied and the number of coincidences was recorded.

A one millicurie Ra source was used with the scintillation counter circuit. A stable operating plateau from twenty to sixty on the discriminator resulted (Fig. II-2). Similarly, a 216 mg Po-Be source was used with the neutron circuit and a stable operating plateau from twenty to sixty on the discriminator was obtained (Fig. II-3). Consequently discriminator settings of forty were used throughout the experiment.



Voltage Characteristic of the
Scintillation Counter Circuit.



Voltage Characteristic of the
Neutron Counter Circuit.

CHAPTER III

EXPERIMENTAL PROCEDURE

In all cases, the long counter was placed at an angle of zero degrees from the point of proton impact upon the target, but the gamma ray counter was placed at varying angles, in such a manner that there would be no interference with the long counter.

The Rockefeller Generator was started and readings of the simultaneous neutron and gamma counts were taken for a given change in charge units as indicated by the beam current integrator, while the proton energy, as indicated on the generating voltmeter, was held constant. This procedure was repeated at desired proton energies. Standard operating procedure was to take readings as the voltage was increased and then to repeat those readings coming down in voltage to verify the data. Since the ability to read the generating voltmeter was greater than its inherent accuracy, this manner of taking data was satisfactory.

During all runs, the elapsed time was noted, as well as the absolute time. This was essential since the determination of the half life of N^{13} obtained from the $C^{13}(p,n)N^{13}$ and $C^{12}(d,n)N^{13}$ reactions was desired.

In general, a beam current of approximately five-sevenths of a microampere was maintained throughout all runs.

Except when the tantalum and potassium targets were used,

the readings beyond threshold had a statistical accuracy of $\lesssim$ 1%. The counting rates with tantalum and potassium were very low and a statistical accuracy of $\lesssim$ 5% was accepted.

In all cases, detecting equipment was placed in the horizontal plane of the target. The instrument positions are given on the individual drawings.

CHAPTER IV

EXPERIMENTAL RESULTS

Thick Carbon Target

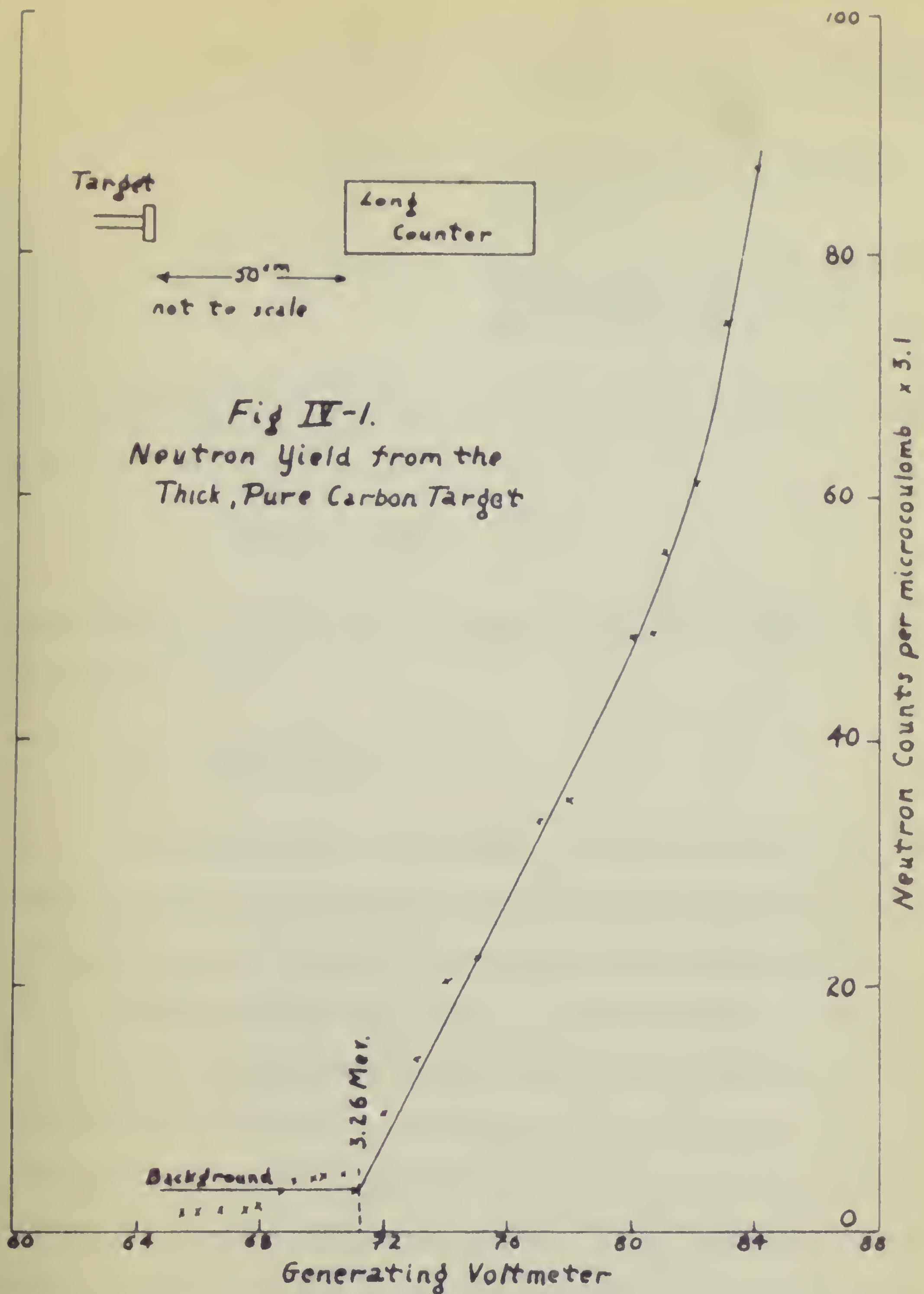
The thick target was obtained from a piece of a rolled and pressed graphite rod, one inch in diameter, machined to nine-sixteenths of an inch and cut into a disk three-eighths of an inch thick. The carbon was inserted into a stationary target, using a piece of 10 mil tantalum sheeting as a backing. No adhesive was necessary because the thickness of the disk provided the required stability. The carbon used was pure graphite to one part in a million (Bu 50).

The plot of the neutron counts per microcoulomb for this thick target, Figure IV-1, showed a negligible background, undisturbed until the threshold of a reaction yielding neutrons occurred at a generating voltmeter setting of 71.2, with an excitation energy of approximately 3.26 Mev ± 1%. Previous experimenters have shown that when ordinary carbon is bombarded with protons, C^{13} is the isotope responsible for the neutron yield (Hax 40a,b).

Using the equation for the determination of the Q value of a reaction,

$$Q = E_2 \left(1 + \frac{A_2}{A_3}\right) - E_1 \left(1 - \frac{A_1}{A_3}\right) - \frac{2(A_1 A_2 E_1 E_2)^{1/2}}{A_3} \cos \theta \; ; \quad \text{(Ev 47)}$$

where


Target
Long Counter
50 cm
not to scale
Fig IV-1.
Neutron Yield from the Thick, Pure Carbon Target
3.26 Mev.
Background
60
64
68
72
76
80
84
88
Generating Voltmeter
0
20
40
60
80
100
Neutron Counts per microcoulomb x 3.1

A_T, A_C, A_1, A_2, A_3 = mass number of target, compound, projectile, product, and residue nuclei respectively;

E_1, E_2, E_3 = kinetic energy of projectile, product, and residue nuclei respectively;

and M_T, M_1, M_2, M_3 = exact masses of target, projectile, product, and residue nuclei respectively;

and knowing that at threshold, $E_2 = 0$ and $\theta = 0^\circ$, the following simplification results:

$$Q = -E_1 \left(1 - \frac{A_1}{A_3}\right) .$$

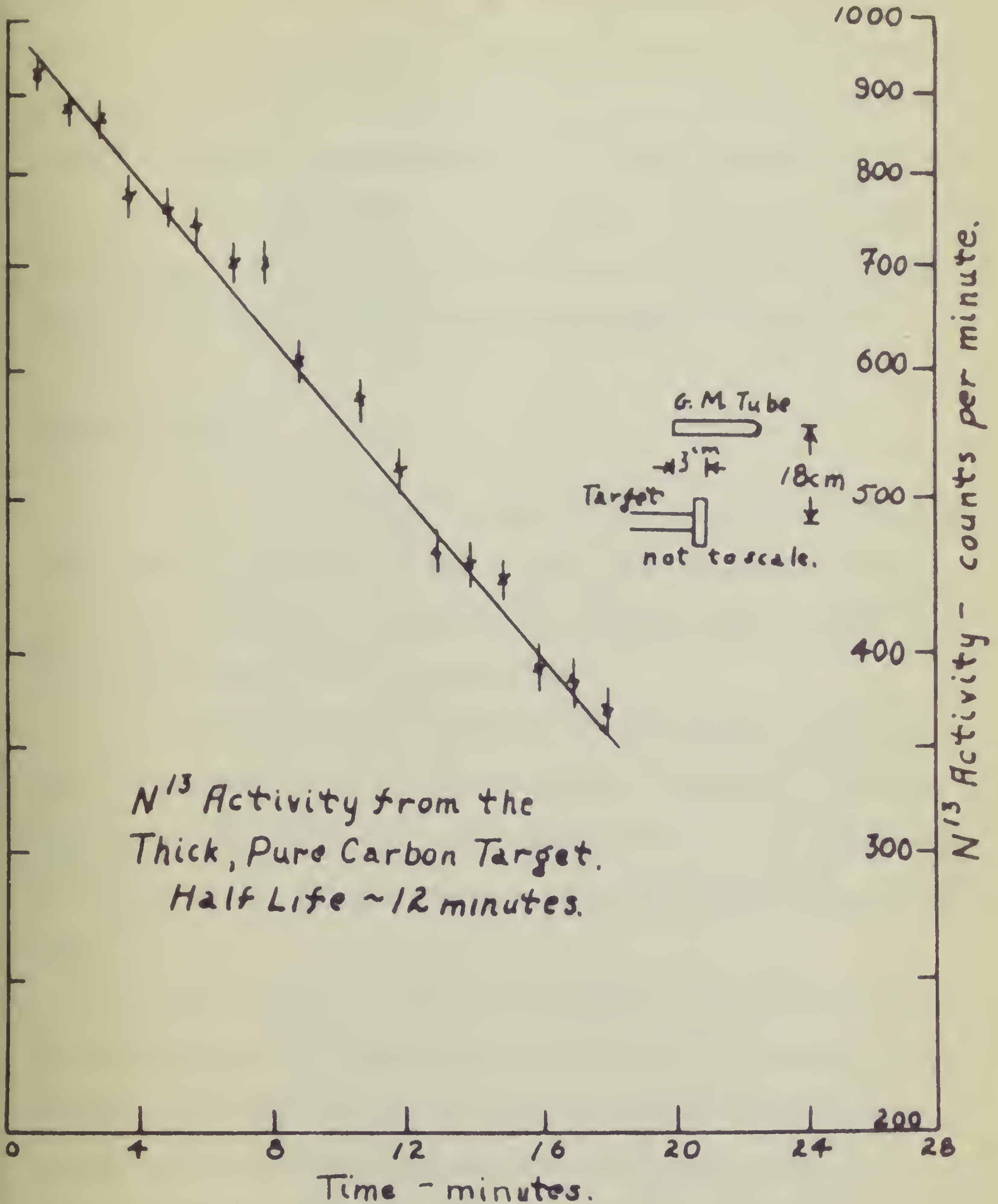
Substituting the proper values from the experimental evidence of the $C^{13}(p,n)N^{13}$ reaction,

$$Q \sim -3.01 \text{ Mev} \pm 1\%.$$

This result was a satisfactory corroboration of the reaction Q value of -2.987 Mev ± 0.1% calculated from the 3.236 Mev ± 0.1% threshold reported by Richards and Smith for the reaction (Ri 50).

Further verification that the neutrons actually resulted from the $C^{13}(p,n)N^{13}$ reaction was obtained when the generating voltage of the Rockefeller Generator was returned to zero at the end of the run, and the activity of the thick target, as detected by a Geiger-Mueller Counter, was observed. The semi-log plot, Figure IV-2, gave a half-life of 12 ± 2 minutes compared to the accepted N^{13} half-life of 9.93 ± 0.03 minutes (Wa 39). $C^{13}(p,n)N^{13}$ is the sole reaction involving the thick target constituents which yields an activity with a half-life of this magnitude (Se 48).

The gamma ray curve, on the other hand, indicated a continuous



1000
900
800
700
600
500
400
300
200
0
4
8
12
16
20
24
28
Time - minutes.
N^{13} Activity - counts per minute.
G. M Tube
3 cm
18 cm
Target
not to scale.
N^{13} Activity from the Thick, Pure Carbon Target. Half Life ~12 minutes.

Fig IV-2.

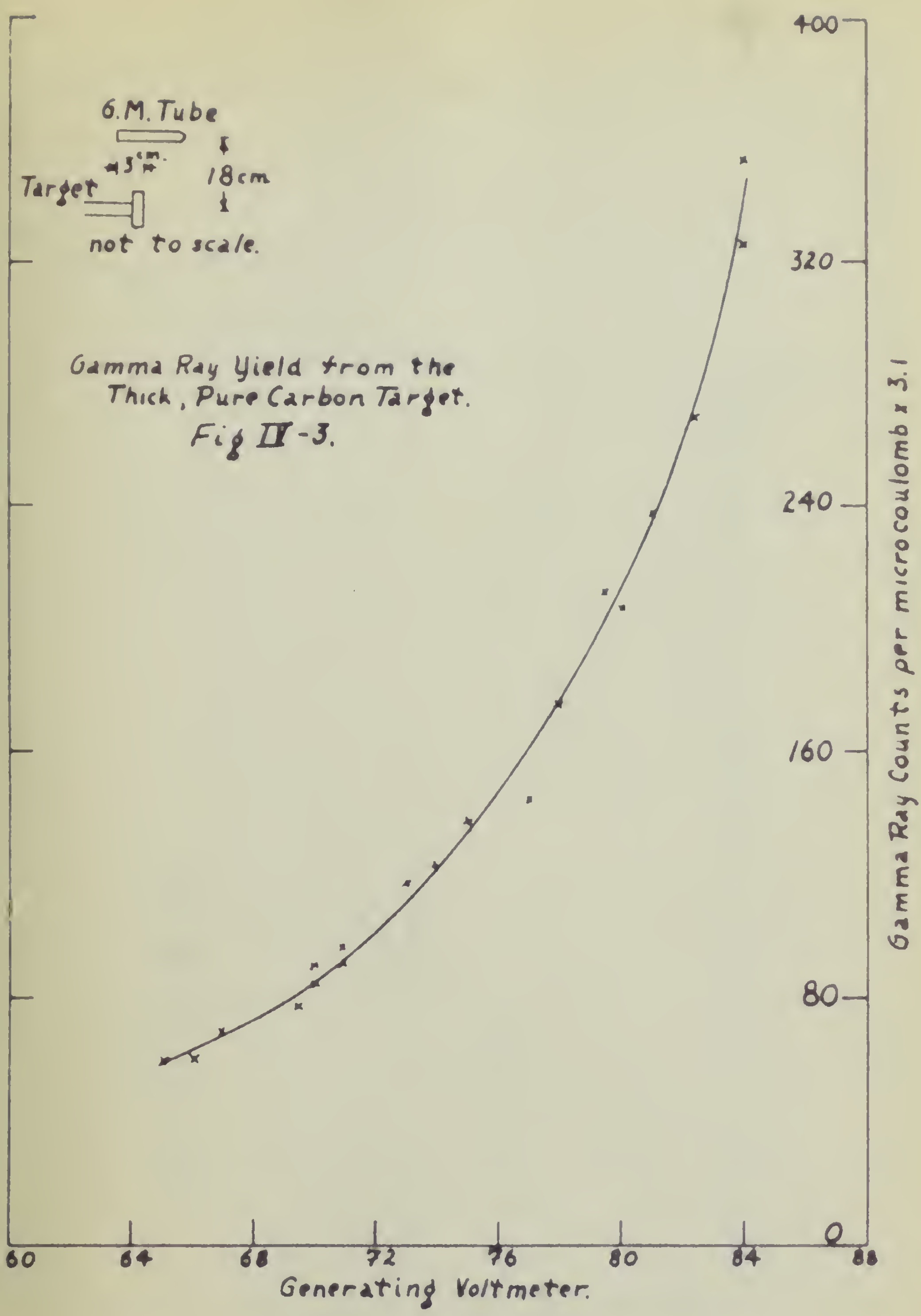
rise in activity with proton energy, with no resonances or other significant features. This gamma ray yield, Figure IV-3, can be attributed to the $C^{12}(p,\gamma)N^{13}$ and $C^{13}(p,\gamma)N^{14}$ reactions (Coc 34), (Ro 38), (Bai 42), and to the gamma ray background caused by protons impinging upon portions of the generator, or upon the grease in the vacuum system which may have been collected on the various slits or have been deposited on the target during the bombardment. The minimum stable operating energy of 1 Mev prevented observation of the level for gamma ray emission occurring at a proton energy of 0.554 ± 2 Mev (Fo 49).

Tantalum Target

A new, clean tantalum backing plate was used as a rotating target and the resulting neutron and gamma ray yields were obtained, to show that the effects obtained with the thick carbon target could not be attributed to the tantalum backing.

The plot of the neutron counts, Figure IV-4, showed that a very low background rate was obtained until a generating voltmeter setting of approximately 71.5 was reached, giving an excitation energy of 3.27 Mev ± 1%. Beyond this point the neutron counts increased markedly.

The resultant activity was negligible compared to that obtained from the thick carbon target, as further substantiated by the fruitless attempts to measure N^{13} activity. Since the tantalum used was mill grade metal with a maximum of 0.03% carbon (Sp 50), the rise in the exceedingly small tantalum background was attributed to the C^{13} in the tantalum and to the effects of carbon from the grease in the vacuum system.



G.M. Tube
3 cm.
18 cm
Target
not to scale.
Gamma Ray Yield from the Thick, Pure Carbon Target.
Fig III-3.
Gamma Ray Counts per microcoulomb x 3.1
Generating Voltmeter.
0
80
160
240
320
400
60
64
68
72
76
80
84
88

The curve of the gamma ray counts, Figure IV-5, again was smooth and of very negligible proportions, yielding only information of a negative nature, i.e., that there was no proton-gamma ray reaction from tantalum. These observations corroborate and extend the observations of Taschek and Hemmendinger, namely, that no activity of any kind was induced in tantalum with protons of energies up to the maximum (3.96 Mev) (Ta 48).

Unenriched Potassium Cyanide Target

A thin layer of potassium cyanide was evaporated in vacuo upon the tantalum backing of a rotating target. A very thin layer of gold was deposited atop the cyanide to prevent volitilization and resultant contamination of the Rockefeller Generator.

The completed unenriched potassium cyanide target was placed upon the rotating target section of the generator and the appropriate readings were taken.

The neutron count - proton energy curve was smooth (Figure IV-6), showing that the thin layers of ordinary potassium cyanide and gold had no appreciable neutron yield and exhibited no resonances.

Attempts to ascertain the presence of N^{13} activity from the unenriched target were fruitless.

The gamma ray curve, Figure IV-7, again was a smooth curve being devoid of information concerning a possible proton-gamma ray reaction.

To insure that the above results were correct, the experiment was repeated at a later date using the same target, and the results obtained duplicated the previous information and curves. In

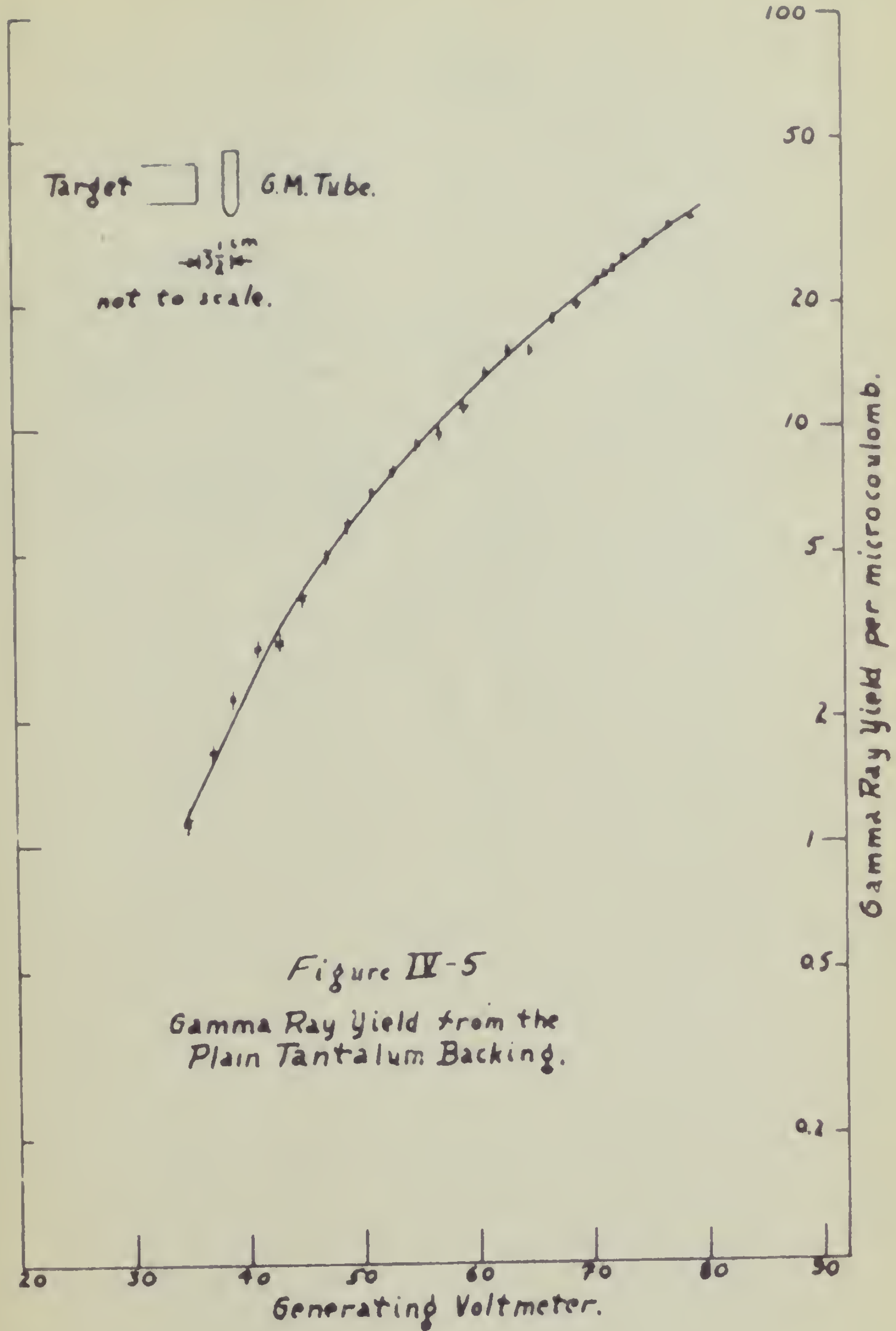
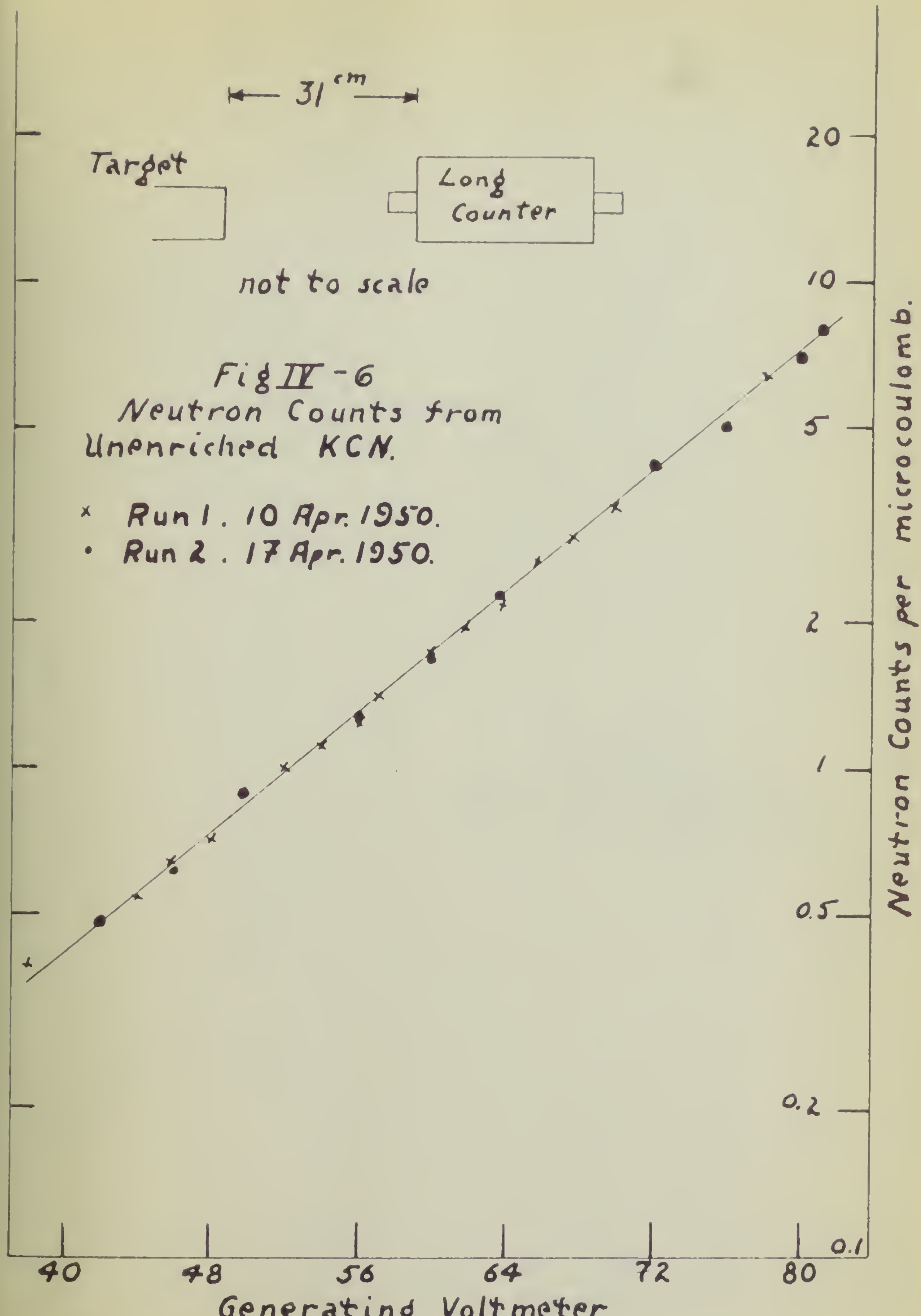


Figure IV-5

Gamma Ray Yield from the Plain Tantalum Backing.



31 cm
Target
Long Counter
not to scale
Fig IV -6
Neutron Counts from Unenriched KCN.
× Run 1. 10 Apr. 1950.
• Run 2. 17 Apr. 1950.
20
10
5
2
1
0.5
0.2
0.1
Neutron Counts per microcoulomb.
40
48
56
64
72
80
Generating Voltmeter

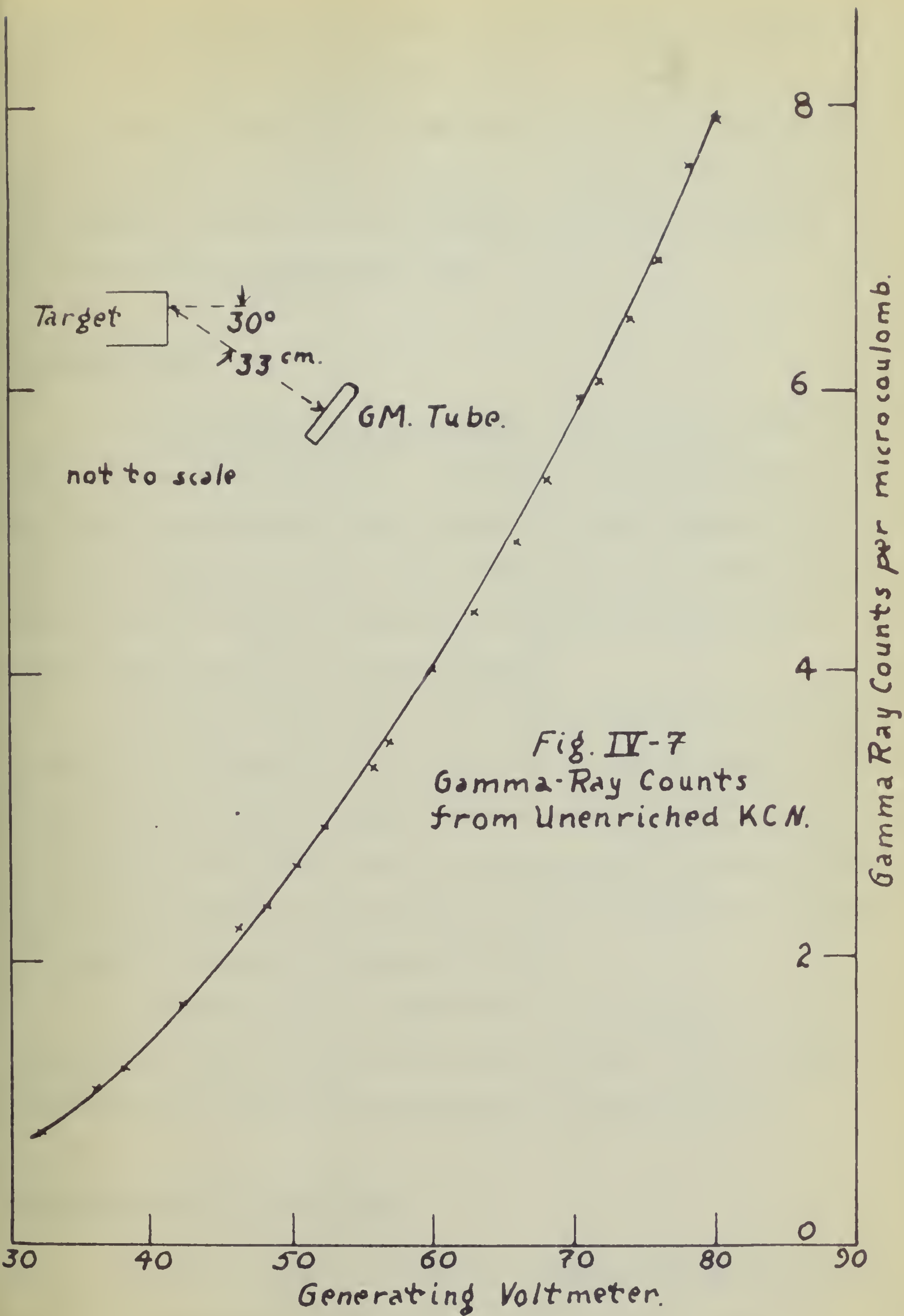


Fig. IV-7
Gamma-Ray Counts
from Unenriched KCN.

addition, a second target was prepared in the same manner as before, which gave the same results described above.

Richards and Smith have reported a low neutron intensity from the $K^{41}(p,n)Ca^{41}$ reaction with a threshold of 1.25 ± .06 Mev (Ri 48). The gamma ray background and the techniques used in this experiment prevented verification of Richards' data.

Potassium Target

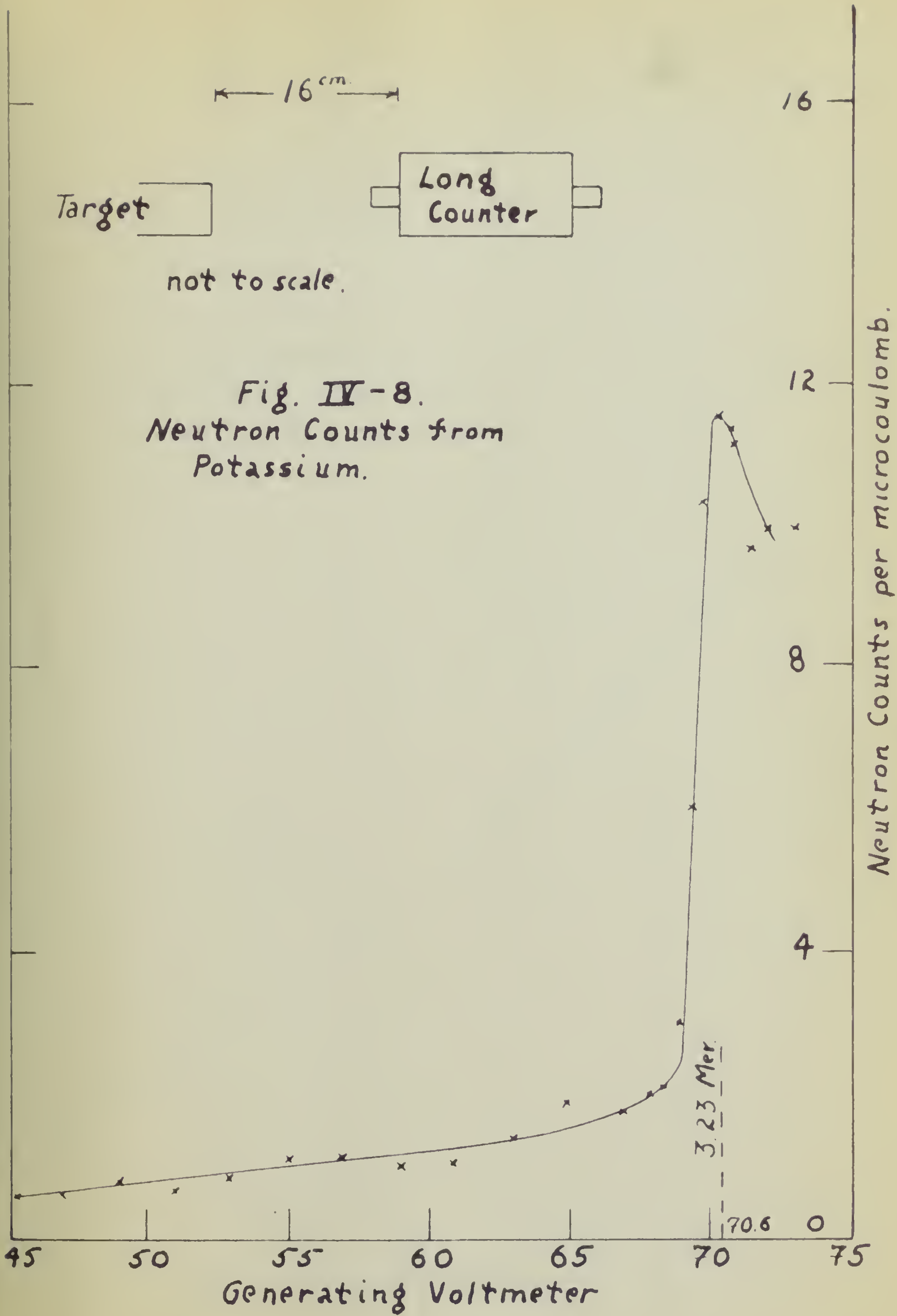
A new electrically heated ceramic oven was placed within the target section of the generator. A small piece of potassium metal was put inside the oven and the target section was sealed and pumped down to vacuum. Heating the oven, using 7 volts AC for five minutes and 10 volts AC for five minutes, resulted in a thin, but plainly visible, layer of potassium upon the tantalum backing.

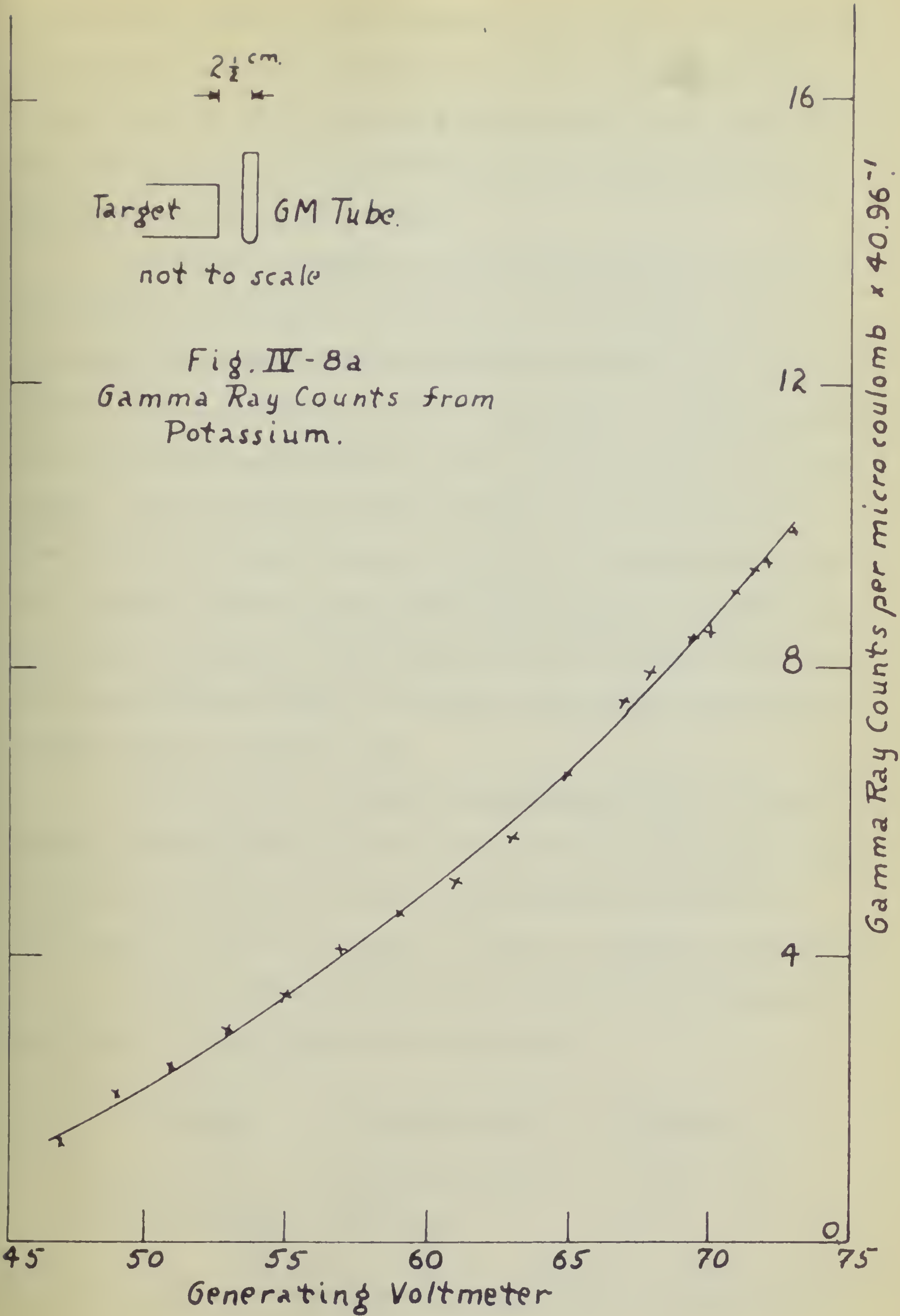
As shown by Figure IV-8, the neutron yield from the potassium could not be distinguished from background at low proton energies. The slight activity detected at higher energies exhibited the same threshold as those of the thick carbon and tantalum targets. Thus the minute amount of C^{13} present was responsible for the yield obtained. Richards' $K^{41}(p,n)Ca^{41}$ reaction was undetected (Ri 48).

The gamma ray curve, Figure IV-8a, was of negligible proportions and the slight activity detected was attributed to the encroachment of the proton beam upon the grease and the generator slits.

Enriched Potassium Cyanide Target

Having shown that the tantalum backing, potassium, and the gold and nitrogen of potassium cyanide target could not cause the re-


16 cm.
Target
Long Counter
not to scale.
Fig. IV-8.
Neutron Counts from Potassium.
3.23 Mev.
70.6
45
50
55
60
65
70
75
Generating Voltmeter
0
4
8
12
16
Neutron Counts per microcoulomb.



$2\frac{1}{2}$ cm.
Target
GM Tube.
not to scale
Fig. IV-8a
Gamma Ray Counts from
Potassium.
16
12
8
4
0
45
50
55
60
65
70
75
Generating Voltmeter
Gamma Ray Counts per micro coulomb x 40.96⁻¹

action obtained from the thick pure carbon, potassium cyanide enriched with sixty-two per cent C^{13} then was used. The rotating target was prepared, with the final anti-volitilization layer of pure gold, using the technique which had been described in the section concerning the unenriched potassium cyanide target.

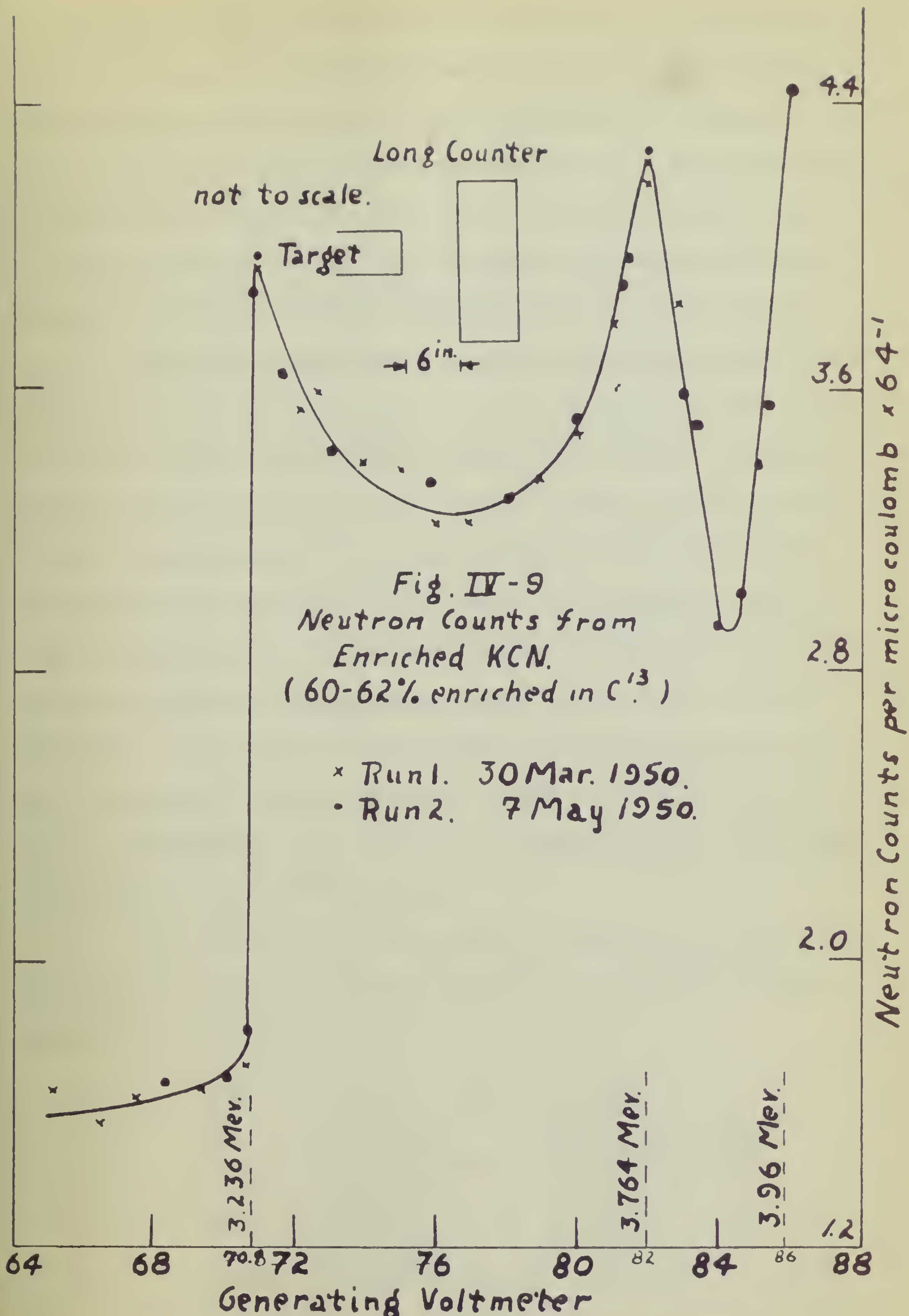
As before, the target was placed upon the target section of the generator and readings were taken. As shown by Figure IV-9, nothing untoward occurred until the generating voltmeter reached 70.8, at which point the neutron yield rose immediately to a very sharp peak with an amplitude approximately two and a half times that of the background. With an increased voltmeter setting, the neutron yield decreased and then increased again to a peak at a voltmeter setting of 82. A further increase of the proton energy resulted in a second dip. The voltage limitations of the machine at that time (March 1950) precluded investigations beyond a voltmeter setting of 84, equivalent to a proton energy of 3.86 Mev $\pm$ 1%.

The sharp rise at 70.8 was the threshold of the $C^{13}(p,n)N^{13}$ reaction, forecast by the results of the thick carbon experiment. According to Richards and Smith, the reaction threshold occurred at 3.236 Mev $\pm$ 1%, which in turn gave a Q value of -2.987 Mev $\pm$ 1% (Ri 50).

The only calibration points for the Rockefeller Generator obtained, prior to March 1950, were the following:

Reaction	Threshold Energy	Voltmeter
$Li^7(p,n)Be^7$	1.882 Mev (He 49)	40.5
$Li^7(H_2^{1+};n,H_1^1)Be^7$	3.764 Mev	82

A voltmeter setting of 70.8, using these two points and in-



Long Counter
not to scale.
Target
6 in.
Fig. IV-9
Neutron Counts from
Enriched KCN.
(60-62% enriched in C13)
× Run 1. 30 Mar. 1950.
• Run 2. 7 May 1950.
3.236 Mev.
3.764 Mev.
3.96 Mev.
4.4
3.6
2.8
2.0
1.2
Neutron Counts per microcoulomb × 64⁻¹
64
68
70.8
72
76
80
82
84
86
88
Generating Voltmeter

terpolating, assuming linearity, was equivalent to 3.25_6 Mev $\pm$ 1%, with a threshold Q value of -3.00_6 Mev $\pm$ 1%. The resultant discrepancy was less than the one per cent accuracy of the generating voltmeter, and since the threshold was sharp, the threshold value of 3.236 Mev for the $C^{13}(p,n)N^{13}$ reaction was accepted, giving another calibration point at a voltmeter setting of 70.8. The linearity of the calibration curve, Figure II-1, permitted extrapolation beyond the calibration points.

Repeating the experiment some two months after the first exploratory run (i.e., in May 1950), it was found that the curve of neutron counts versus proton energy was reproducible, with the threshold again at 70.8 and with a peak again at 82. However, careful attention to the internal pressure in the generator had extended the limit of observations to a voltmeter setting of 86, equivalent to a proton energy of 3.96 Mev $\pm$ 1%. In this new region of investigation, the trough after the second peak was defined and then a sharp rise, as if to a third peak. The second peak occurring at a generating voltmeter setting of 82 (which coincided with the calibration point for 3.764 Mev $\pm$ 1%) was caused by the first level in the excited nucleus of N^{14} available from the $C^{13}(p,n)N^{13}$ reaction.

The accepted value of the masses of the resultant particles were used to find the energy state of (N^{13} + n) in relation to the ground state of N^{14}, i.e.,

N^{13}	=	13.00988 amu	(Cor 47)
n	=	1.00898	(Ev 48, Pg. I-33)
		14.01886	
N^{14}	=	14.00751	(Cor 47)
Δ mass	=	0.01135 amu	

Converted to energy using the mass-energy relationship of 931.1 Mev per atomic mass unit (Ev 48, Pg. I-30), it was found that (N^{13} + n) had a value of 10.57 Mev above the N^{14} ground level.

To find the energy level of $(N^{14})^*$, the following relationship was used:

$$E_{(N^{13} + n)} + E_n = E_{(N^{14})^*} .$$

The neutron energy, E_n, was determined from McKibben's formula where

$$E_n = E_3 = \frac{M_2 M_4}{(M_1 + M_2)^2} \left[E_1 + \frac{M_1 + M_2}{M_2} Q \right], \qquad \text{(Mc 46)}$$

where

M_1, M_2, M_4 $\equiv$ mass of incident, target, and residual nuclei;

E_1, E_3 $\equiv$ kinetic energy of incident and resulting particles respectively;

Q $\equiv$ reaction Q value;

$E_{(N^{14})^*}$ = 10.57 + 0.47 = 10.04 Mev ± 1%;

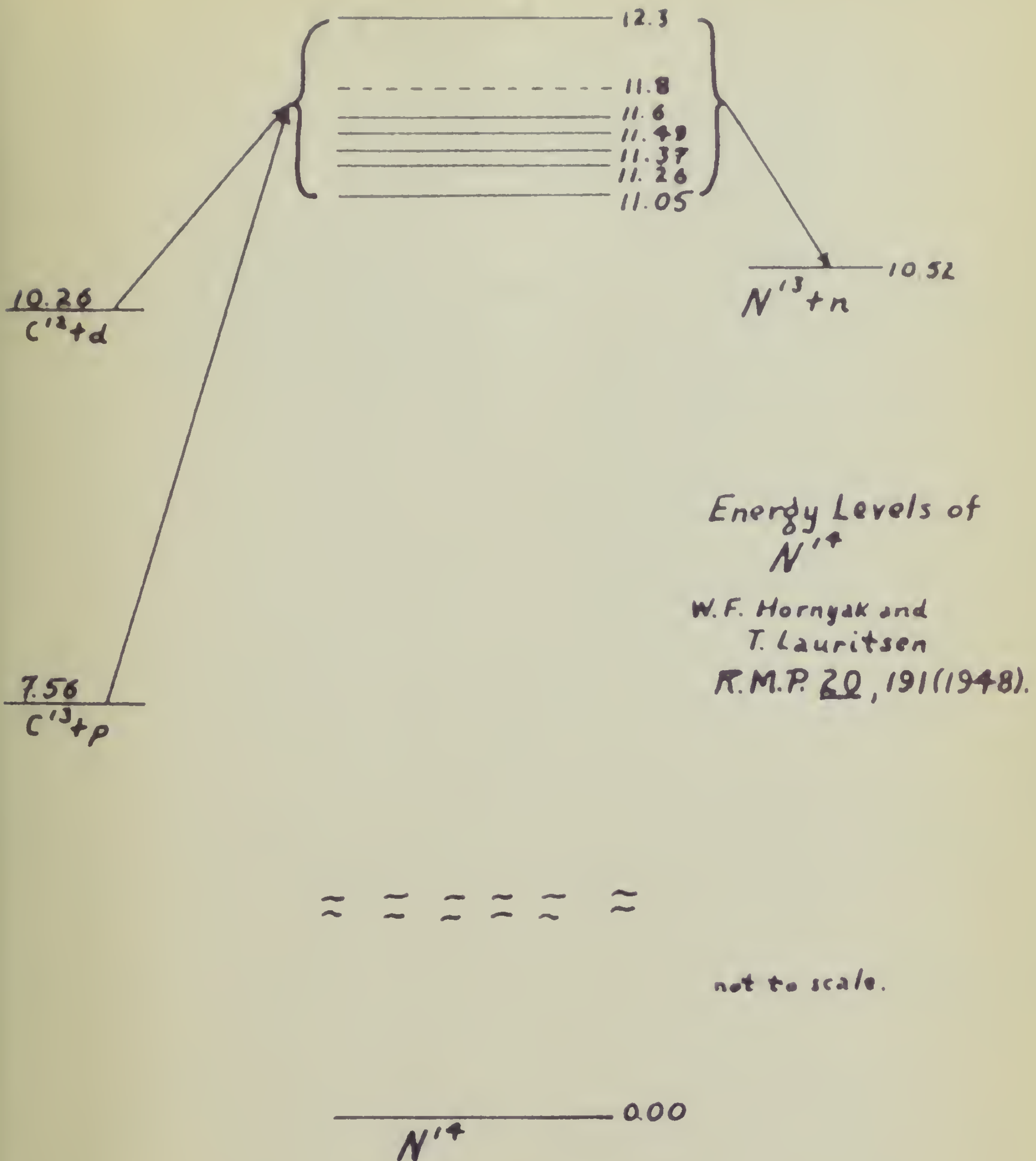
which is in agreement with the value of 10.05 Mev given by Hornyak and Lauritsen for the first energy level in N^{14} which could be excited by the $C^{13}(p,n)N^{13}$ reaction (Ho 48). This sharp resonance at 3.764 Mev ± 1% had a width at half resonance of 45 ± 20 Kev, corroborating the value of 60 Kev reported by Bailey et al. (Bai 42).

The limitations of the machine precluded proton energies exceeding 3.96 Mev. As shown by the curve, Figure IV-9, the neutron yield was rising rapidly at this maximum attainable energy. Bennett et al. (Ben 41) have shown that an excited level in N^{14} exists at 11.26 Mev (Ho 48). Assuming that the activity at the width at half resonance of the second resonant peak was equal to that of the first resonant

peak with a width for this level of 55 ± 20 Kev, and using Figure IV-9, it was found that the second resonance peak would occur at 86.25 with a proton energy of 3.96_5 Mev ± 1%. McKibben's formula (Mc 46) gave a neutron energy $E_n = 0.64$ Mev, indicating a level in N^{14} at 11.21 Mev ± 3%. Hornyak and Lauritsen gave 11.26 Mev for the second level in N^{14} possibly available from the $C^{13}(p,n)N^{13}$ reaction, Figure IV-10 (Ho 48). The assumption of 55 Kev level width was made using Bailey's values of the 60 Kev and 50 Kev for the adjacent levels for neutron emission from the $C^{12}(d,n)N^{13}$ reaction (Bai 42).

The narrow half-width of the first peak obtained by use of the enriched cyanide target indicated that the target thickness was $\lesssim$ 45 ± 20 Kev. Attempts to maintain a constant bombardment of the target at these high energies were of no avail and no N^{13} activity could be detected from the thin target after the runs.

The gamma ray yield, Figure IV-11, obtained from this target was a smooth curve rising continuously with proton energy, as was the case with the thick carbon target, exhibiting no resonances or other significant features. Bennett <u>et al</u>. have reported resonances for gamma ray emission from the $C^{12}(d,n)N^{13}$ reaction corresponding to $(N^{14})^*$ levels at 11.05 and 11.26 Mev (Ben 41). No such resonances were found from the $C^{13}(p,n)N^{13}$ reaction.



Energy Levels of N^{14}

W. F. Hornyak and T. Lauritsen R.M.P. 20, 191(1948).

Fig IV-10.

CHAPTER V

CORRECTIONS TO THE EXPERIMENTAL DATA

The method of investigation pursued was to obtain a threshold measurement using the pure carbon target and, with that knowledge, to determine the background effect of the constituents used in the ordinary potassium cyanide target together with the gold protective casing and tantalum backing, prior to using the enriched potassium cyanide target.

The results of the latter investigations produced no vexatious or startling results, and it was not necessary to apply corrections to the neutron data obtained during the enriched potassium cyanide run.

The same course of investigation was pursued and the same conclusion was reached in the case of the gamma ray yield.

Background was troublesome for low intensity beams of $\lesssim \frac{1}{2}$ μampere giving slight indications of a background directly proportional to the elapsed time of the run. Attempts to evaluate the time function by varying beam intensity for a given voltmeter setting were made. Removal of all radioactive sources, and leakage and non-linearity tests of the beam current integrator eliminated possible explanations of this phenomenon.

CHAPTER VI

SUMMARY

Resonances for Neutron Emission

The data from the thick carbon target showed that the neutrons resulted from the

$$C^{13} + p \longrightarrow (N^{14})^{*} \longrightarrow N^{13} + n + Q$$

reaction, since the Q value of -3.01 Mev ± 1% obtained corroborated the accepted value of -2.98 ± 0.1% (Ri 50), and the half-life of the resultant activity approached that of 9.93 ± 0.03 minutes reported by Ward (Wa 50).

A study of the neutron yield from plain tantalum verified and extended Taschek's and Hemmendinger's conclusion concerning the absence of activity from proton induced reactions with protons of energies to a maximum of 3.96 Mev (Ta 48). However, there was a definite indication of carbon contamination in the tantalum since the $C^{13}(p,n)N^{13}$ threshold was detected by this reaction.

Data obtained from ordinary potassium cyanide covered with a thin layer of gold indicated that no significant neutron emission occurred from the target.

The plain potassium target failed to show the neutron activity reported by Richards and Smith (Ri 50). Carbon contamination again was evident.

Using enriched potassium cyanide (60-62% C^{13}), appreciable neutron emission was detected. Since the possibility of such a yield from all constituents of the cyanide other than C^{13} was eliminated, the neutron activity was attributed to the $C^{13}(p,n)N^{13}$ reaction. The threshold obtained, confirmed that found by Richards (Ri 50). A level in $(N^{14})^*$ at 11.04 Mev $\pm$ 1% and a strong indication of a level at 11.21 Mev $\pm$ 3% were found.

TABLE VI-1

Comparison of $C^{13}(p,n)N^{13}$ Data
with the Literature

Threshold	Experimental	Literature	
E_p	3.25_6 Mev $\pm$ 1%	3.236 Mev $\pm$ 0.1%	(Ri 50)
Q	-3.00_6 Mev $\pm$ 1%	-2.987 Mev $\pm$ 0.1%	

A comparison of the $(N^{14})^*$ levels follows, on the next page.

TABLE VI-2

$(N^{14})^*$ Levels Above the Ground State

		from $C^{13}(p,n)N^{13}$		from $C^{12}(d,n)N^{13}$	
Level Value		11.04 Mev $\pm$ 1%		11.05 Mev	(Ho 48)
Width		45 $\pm$ 20 Kev		60 Kev	(Bai 42)
Projectile Energy	E_p	3.76_4 Mev $\pm$ 1%	E_d	0.92 Mev	(Bon 40b)
Level Value		11.21 Mev $\pm$ 3%		11.26 Mev	(Ho 48)
Width		-----		-----	
Projectile Energy	E_p	3.96_5 $\pm$ 1%	E_d	1.16 Mev	(Bon 40b)

There are definite indications that the resonance level for neutron emission at a deuteron energy of 1.16 Mev from the $C^{12}(d,n)N^{13}$ reaction reported by Bonnor et al. (Bon 40b), which was cast into doubt by Bailey et al. in 1948 (Bai 48), does exist for the reaction, $C^{13}(p,n)N^{13}$.

As shown by the above tables, the first two levels in $(N^{14})^*$ are equally available to the $C^{13}(p,n)N^{13}$ and $C^{12}(d,n)N^{13}$ reactions. Thus the validity of the theoreticist's hypothesis (Br 36), (Boh 36), (Bet 37), (Bet 47), concerning the invariance of energy levels in a nuclide, regardless of the manner by which the nuclide is formed, provided the nuclear selection rules are not violated, is verified for these two levels in N^{14}.

Lifetimes of the $(N^{14})^*$ Levels

An estimate may be obtained of the time the compound nucleus

$(N^{14})^*$ exists prior to neutron emission, using the uncertainty relationship,

$$\Delta E \Delta t \simeq \frac{h}{2\pi} \qquad \text{(Ev 48, Pg. I-117)}$$

$$\Delta t \simeq \frac{1.04 \times 10^{-27}}{1.6 \times 10^{-6} \, \Delta E(\text{Mev})}$$

giving

$$\Delta t_{11.04} \simeq 1.5 \times 10^{-20} \text{ sec.}$$

An estimate of the lifetime of the $(N^{14})^*$ state can be made from the relation,

$$\Delta t' \simeq \frac{2R}{v} ; \qquad \text{(Boh 36)}$$

where R is the nuclear radius of $N^{14} \sim 1.5 \times 10^{-13} A^{1/3}$ cm. = 3.6×10^{-13} cm., and v is the neutron velocity = $\sqrt{\frac{2E_n}{m_n}}$ cm/sec., where E_n is the neutron energy from McKibben's formula (Mc 46), i.e.,

$$\Delta t'_{11.04} \simeq \frac{2 \times 3.6 \times 10^{-13}}{9.5 \times 10^{8}} = 7.6 \times 10^{-22} \text{ sec.}$$

The ratio of the lifetimes from the above calculations is

$$\left[\frac{t}{t'}\right]_{11.04} \sim 20$$

This ratio is reasonable in view of the time required for energy exchange within the compound nucleus, postulated by the Bohr theory of the compound nucleus (Bo 36), although Bennett obtaining similar results stated the possibility that the ratio might be attributed to a selection rule (Ben 41).

Gamma Yields

The uninteresting results obtained by use of the Geiger-Mueller detector indicated an absence of resonance phenomena, although previous experiments (Bon 40a,b), (Ben 41), (Ri 48), (Va 49), etc., had found definite indications of $C^{12}(p,\gamma)N^{13}$ and $C^{13}(p,\gamma)N^{14}$ reactions. A more efficient counter and a more careful evaluation of the background existing in the generator target room is necessary prior to repeating the above experiments. On the basis of the results obtained, one could not state as to the possible existence of levels in $(N^{14})^*$ from the $C^{13}(p,\gamma)N^{14}$ reaction over the energy range studied.

Suggestions for Further Work

In the near future, it is expected that the maximum available proton energies will be extended appreciably beyond 4 Mev. It would be informative to continue the investigation of the $C^{13}(p,n)N^{13}$ reaction to higher energies, verifying the exact energy location of the second resonance and of any higher resonances. A comparison of the levels of $(N^{14})^*$ with those found for the $C^{12}(d,n)N^{13}$ reaction would be of great interest.

With increased stability of operation at these higher proton energies, longer target bombardments would become practical, enabling a precise determination to be made of the N^{13} activity beyond each level.

A more careful investigation of the gamma ray yields from the various targets would be of interest in order to confirm the $C^{13}(p,\gamma)N^{14}$ reaction most recently reported by Fowler and Lauritsen

(Fe 49). Moreover, any gamma ray resonance levels obtained could be compared with the levels for neutron emission yielding information concerning selection rules, etc., invoked by the respective processes.

APPENDIX I

ELECTRONIC CIRCUIT DIAGRAMS

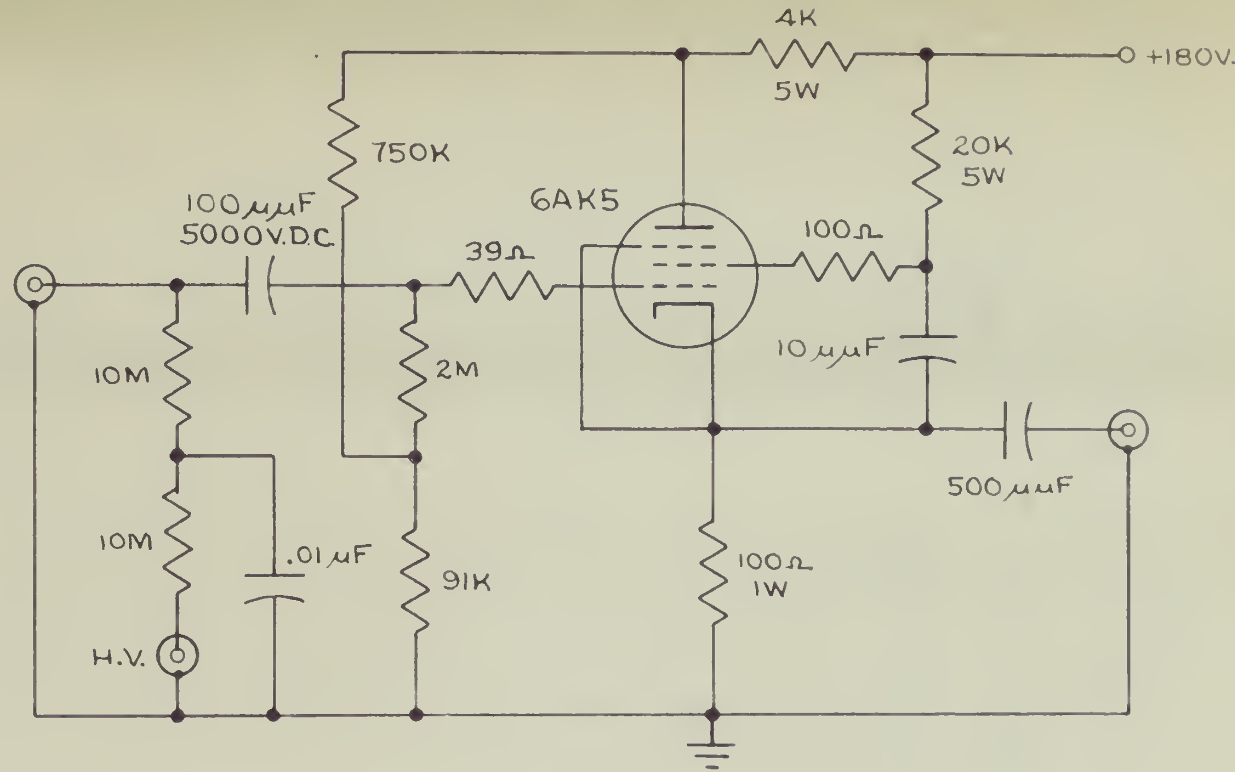


FIG. A-1 BF_3 COUNTER PREAMPLIFIER

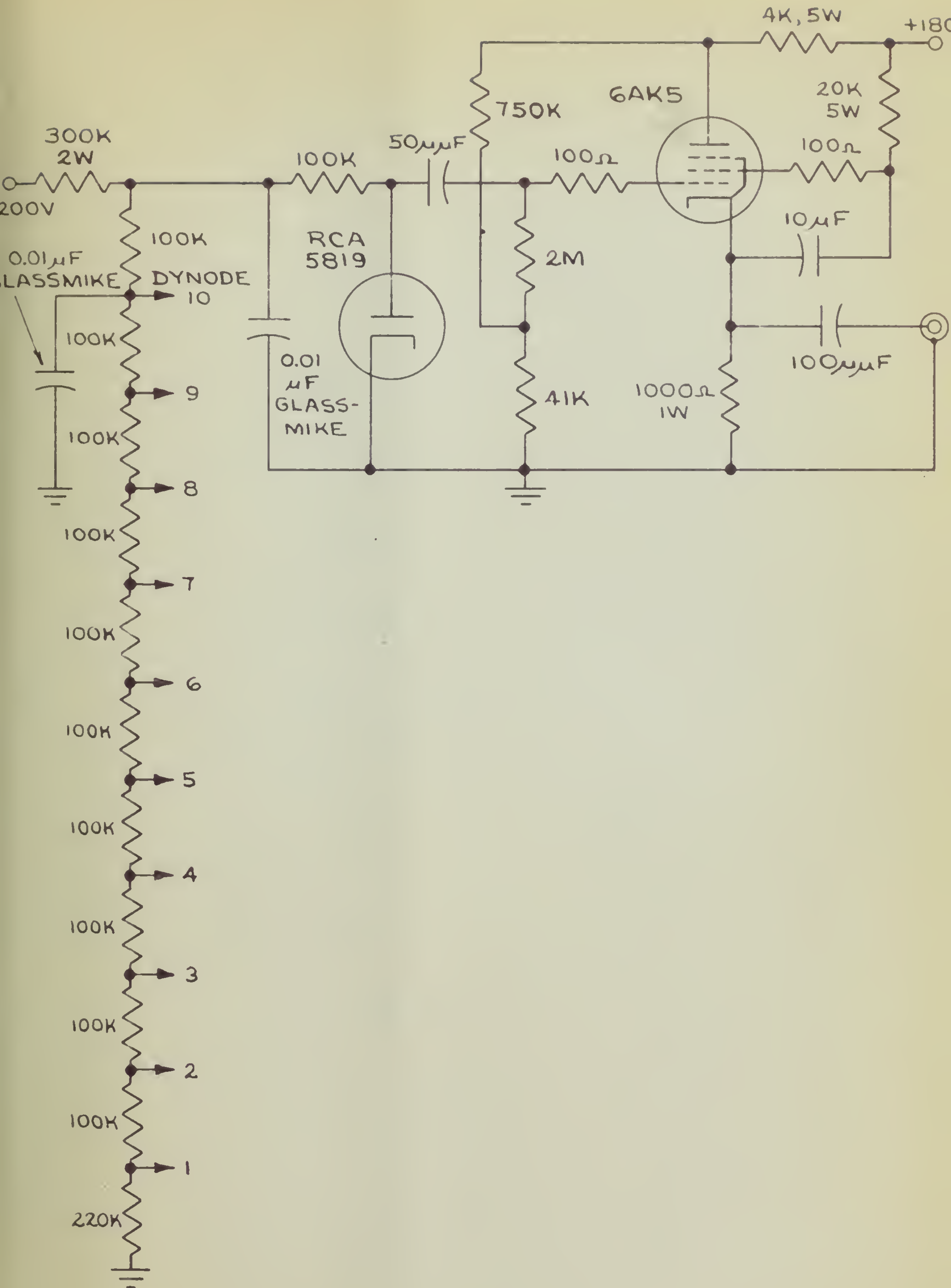


FIG A-2 SCINTILLATION COUNTER PREAMPLIFIER

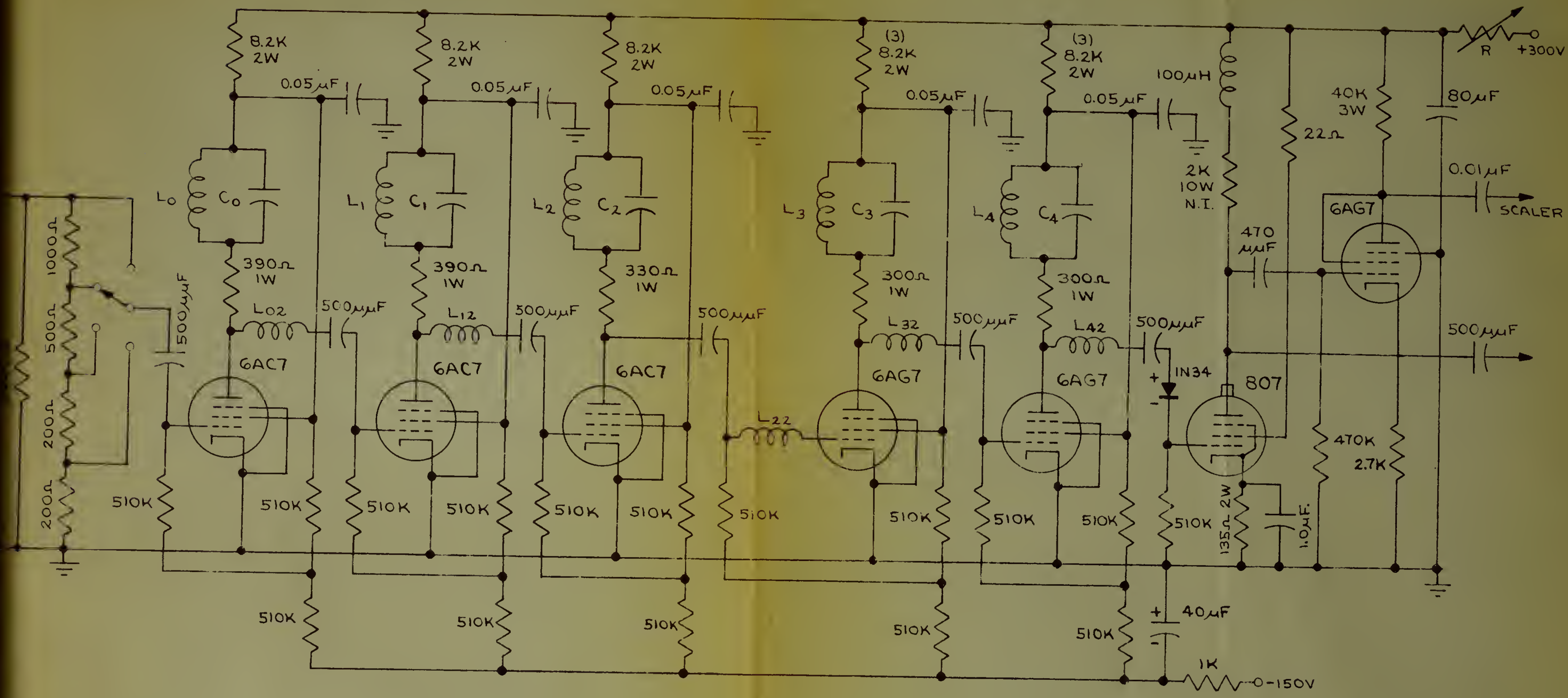


FIG. A-3 FAST PULSE AMPLIFIER

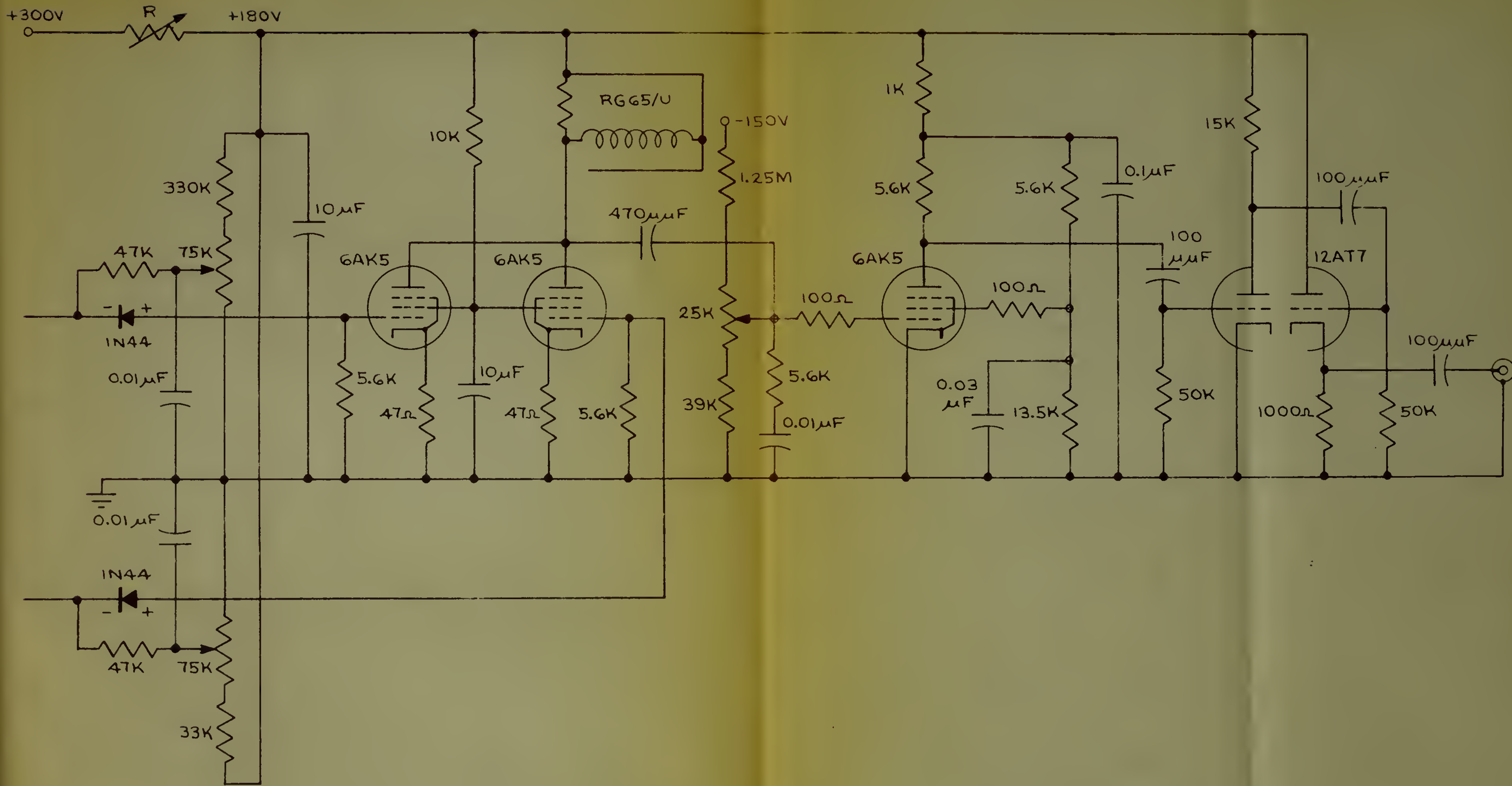


FIG. A-4 COINCIDENCE CIRCUIT

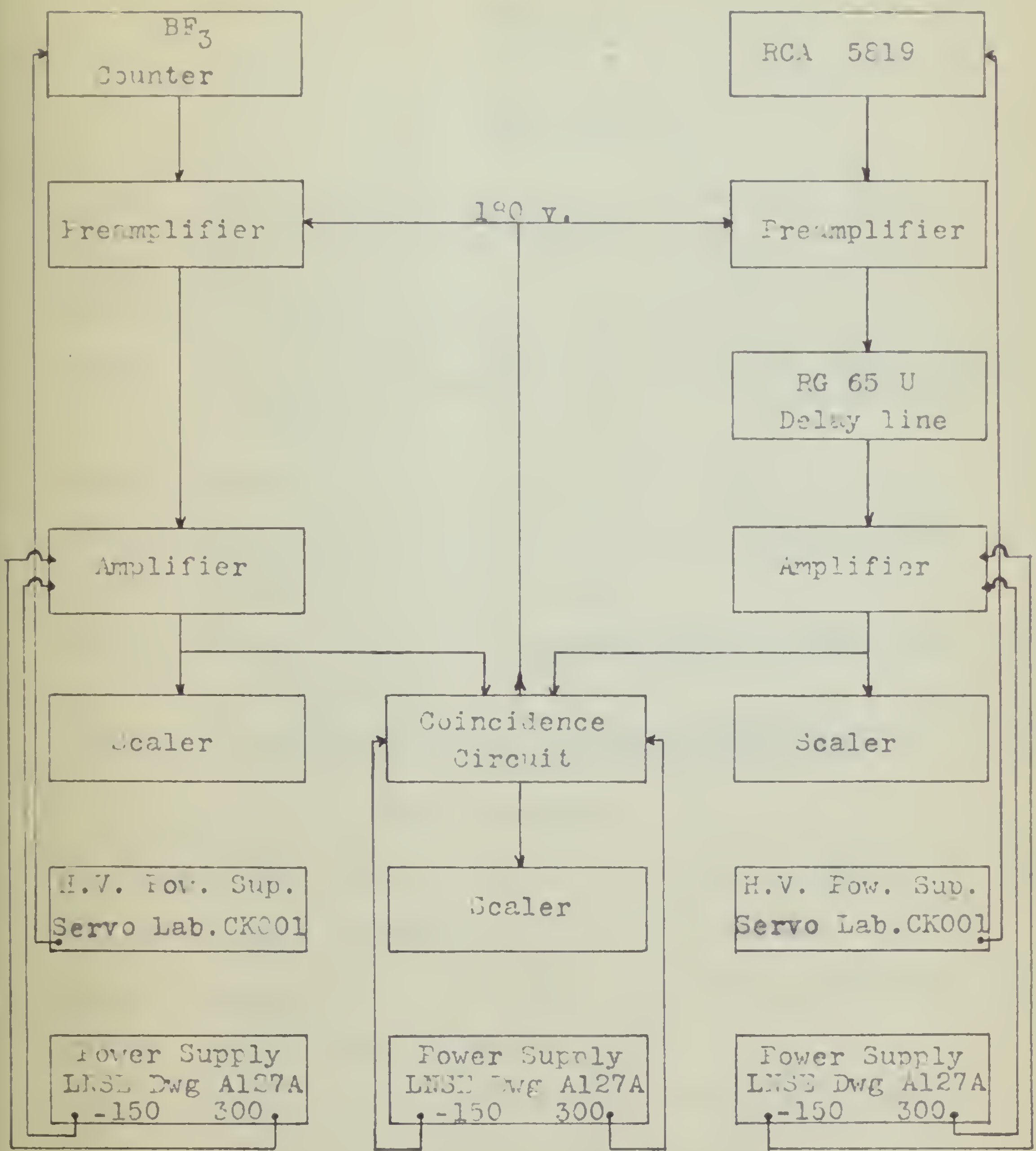


Fig. A-5. Block diagram of the complete coincidence counting system.

APPENDIX II

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c.1 A study of excited states of N^{14} from the $C^{13}(p,n)N^{13}$ reaction.

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